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Comprehensive Monitoring and Evaluation of Ballast Tank Coatings Integrity for Life Prediction and Condition Based Maintenance

K.E. Lucas

Naval Research Laboratory
PO Box 1739
Key West, FL

P.F. Slebodnick
E.D. Thomas

Center for Corrosion and Engineering Branch
Chemistry Division

E.A. Hogan

GEO-Centers, Inc.
PO Box 1739
Key West, FL

A.I. Kaznoff

Naval Sea Systems Comand
Director of Materials Engineering
Arlington, VA

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K.E. Lucas,* P.F. Slebodnick, E.A. Hogan,** E.D. Thomas, and A.I. Kaznoff***

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*Naval Research Laboratory, PO Box 1739, Key West, FL 33041-1739
**GEO-Center, Inc., PO Box 1739, Key West, FL 33041-1739
***Naval Sea Systems Command, Director of Materials Engineering, Arlington, VA

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Navy maintenance costs for seawater ballast tank preservation continue to increase, concurrent with a corresponding growth in the time interval between overhaul cycles. To reduce the high cost of manned seawater ballast tank inspections, corrosion potential and current sensors have been developed to monitor changes in the tank cathodic protection levels and zinc anode current requirements over time. When combined with remote optical inspection capability, currently under development, a comprehensive monitoring program will be established. This will provide for in-situ long-term monitoring of tank corrosion combined with periodic visual inspections to document tank coating condition. The goal of this effort is to provide a tank husbandry program for direct monitoring, identification, and ranking of individual tanks in terms of condition, maintenance or overhaul requirements, without the need for costly periodic manned inspections.

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COMPREHENSIVE MONITORING AND EVALUATION OF BALLAST TANK COATINGS INTEGRITY FOR LIFE PREDICTION AND CONDITION BASED MAINTENANCE

INTRODUCTION

A typical ballast tank preservation scenario utilizes coatings as the primary corrosion barrier with cathodic protection as a secondary measure to minimize coatings degradation and to prevent the possible destructive effects of galvanic corrosion [1]. Most tank maintenance problems fall into several categories often related to the operational aspects of the ship and are roughly identified as:

a) Corrosion/structural damage in seawater ballast tanks
b) Osmotic disbondment caused by condensation on overhead surfaces
c) Coatings degradation caused by normal deterioration, variable tank levels, wet/dry cycling or depletion of cathodic protection
d) Failure related to substandard coatings application or specification.

In addition, the geometry is often unique for each tank and maintenance is complicated by many complex structural members and baffles. Working conditions, where maintenance is typically needed, are often difficult and provide less than ideal coatings quality assurance scenarios.

Shipboard tanks and voids make up a significant percentage of below deck space and are necessary components for normal operation pertaining to seawater buoyancy control, damage control, seawater compensated fuel storage, and a number of other essential tasks, such as combined holding (CHT), potable water storage and sludge. The size and quantity of these tanks vary considerably for each class of ship, with the typical numbers of tanks per ship in excess of 300 for carriers, 75-100 for cruisers or destroyers and up to 75 large tanks in amphibious assault ships. Operationally, each tank may see different degrees of service depending on mission requirements, thus creating widely variable maintenance concerns, in addition to those problems routinely anticipated for each tank type. As a result, up to 50% of tank maintenance is due to hidden damage or unplanned work.

The maintenance of tanks is more than just re-painting the metal surfaces, because tank inspection and assessment alone requires the need for manual opening, gas freeing, staging (if necessary) and entry of trained personnel. Thousands of tanks are inspected yearly, with the average cost of an individual tank inspection at approximately $8-15 thousand/each. For this, each tank must inspected at least once every dry dock cycle, or nominally at least every 5 to 7 years depending on service or ship class. Once tanks are identified for refurbishment, costs soar to over $250 million/year to perform the maintenance. This covers only a fraction of the thousands of Navy tanks in service. Of these costs, which provide for staging, surface preparation, and coatings application, dollars should be spent on those tanks in the worst condition. For this methodology to work effectively, all tanks should be monitored, assessed and correctly identified for maintenance only when the condition of the preservation warrants repair.

As part of larger Navy Condition Based Maintenance (CBM), Engineering for Reduced Maintenance (ERM) and Capital Investment for Labor (CI Labor) initiatives, the purpose of this program was to provide a technique/methodology to enable the measurement of the "state of preservation" of shipboard tanks and to predict maintenance requirements with minimal invasive inspection and costs. This concept thus provides for: 1) the definitive assessment of long-term tank preservation along with a "red-yellow-green" decision making process aimed at *ranking* tank deterioration verses other tanks, and 2) qualification of overall tank condition for the actual scheduling of refurbishment and maintenance. It is clear that the development of a remote tank assessment capability would greatly reduce the maintenance burden associated with manned tank inspections, and correspondingly, would focus limited fleet maintenance dollars to only those tanks which require immediate attention.

This research effort has addressed the problem of tank assessment from two directions. The first has been the development of durable in-situ corrosion sensors to measure the overall state of cathodic protection, which are used to determine the relative degradation of coatings over time [2]. This approach focuses on the integrity of the coatings "system" or tank condition as a whole, and provides significant long-term data relative to sacrificial anode life and to the gradual changes in overall coatings properties. The second aspect of the tank assessment was to develop a "smart" remote inspection platform [3, 4, 5], which could provide "ground truth" and visual data, similar to that a tank inspector would collect. This system, when used either stand-alone or as part of the corrosion sensor monitoring system, provides an objective visual analysis of tank condition and can be used to evaluate coatings integrity. This inspection ideally would be necessitated only by condition based measurements and would replace the need for routine manned visual inspections to assess coating or cathodic protection integrity.

This paper presents results of ongoing work, concerned with the development of corrosion sensor technology and portable shipboard inspection instrumentation. Corrosion sensor results and discussion are presented concerning data

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collected from sensors in several test ships and multiple ballast tanks. The remote visual inspection technique will be discussed in terms of instrumentation requirements and capabilities for analyzing coatings degradation in small and large confined spaces. Discussion will be limited to seawater ballast tanks and compensated fuel tanks.

EXPERIMENTAL

Corrosion Sensors

Figure 1 shows a schematic representation of a prototypical tank reference cell installation. For each sensor, a minimum of two reference cells are suspended in the tank, with one always residing near the bottom, while the others are arranged to correspond to intermediate and filled states. Upon filling, the lower water reference cell registers the change in potential almost immediately as the tank fills. The upper reference cells begin to read once the water reaches them. The upper areas of the tank will be better indicated on these cells and will report the relative time it takes to fully polarize and protect these areas. These sensors can be installed with minimal impact to the tank and provide continual in-situ performance data whenever the tank is filled or when seawater displaces the fuel in a compensated fuel tank. Sensors can be installed in a variety of forms and data handling configurations, from completely internal watertight systems to fully integrated computerized ship systems.

Figure 2 shows a schematic of an instrumented zinc anode, which is placed into the tank to provide the anode current output during all test periods, including any residual water and all filled states. Rather than direct attachment, the zinc anode is insulated from the structure and electrically grounded through a 0.1 ohm shunt resistor to the tank wall. The voltage drop across the resistor translates (10X) to current output for monitoring purposes. Use of the instrumented zinc in this way allows it to behave in a manner similar to the actual tank anodes and enables a good estimation of total tank cathodic protection current output to be calculated. The anodes used are of either a ZHC-23 or ZSS-24 type, manufactured in accordance with MIL-A-18001K.

Over 30 tanks to date were instrumented with the corrosion sensor and zinc anode combination. Both long-term anode current output and potential measurements from the reference cells were recorded on datalogger units. Dataloggers were located either strategically within the tanks or at remote locations external to the tank. Data from each tank were collected hourly and later compiled for analysis. Additionally for this work, tank level indicators (TLI) were installed, to document the tank filling evolutions and to provide detailed operational data, as shown in figure 1.

Inspection Instrumentation

Table 1 shows the various technologies considered for use in the remote tank inspection platform and provides the pros and cons associated with each technique. Consideration for this inspection platform went beyond the scientific capability of the technique and looked at the practical aspects and overall cost/benefits that each technique could provide. These aspects included: rapid assessment capability, impartiality, repeatability and the provision such that data could be integrated directly into an assessment algorithm. Technically, factors which strongly influenced coatings assessment and integrity are as follows: 1) coatings failure percentages, 2) defect percentages, such as blistering, or cracking, 3) adhesion loss, 4) coatings moisture saturation and indirectly 5) cathodic protection.

Two instrumentation packages are being designed which will provide for the inspection of tanks, in either a filled or empty state. A schematic example of the inspection packages are shown in figure 3. The instrument platforms designed for use within ballast tanks will be utilized for tanks which are often empty in port or can be reduced in liquid volume to facilitate tank inspection. Typically, a tank inspection platform will be installed in a hatch opening and will be lowered into an empty tank via an extending arm, enabling a view of the walls, ceiling and proximal components. Tanks which cannot be emptied, cannot host the hatchable unit or those which must remain full can be inspected using a remotely operated vehicle (ROV) equipped with associated instrumentation. Data are intended to be analyzed real-time during the inspection and compared concurrently with the corrosion sensor/instrumented zinc data, where applicable.

The prototype inspection units have optical band CCD cameras, capable of providing visual imaging and real color analysis. Tilt, pan and zoom features allow for versatility and for the capability to incorporate computerized control of imaging functions. By integrating the computerized control algorithm, data analysis and recording option into the system, tanks can be repeatedly inspected, in an objective manner, with minimal operator assistance. Images can be spectrographically analyzed and used for the assessment of coatings damage percentages, defects and appearance. Visual imaging provides the basis for the current inspection package, but the platform has the capability for the continual upgrade and for the addition of other analytical equipment.

To date, the visual analysis platform has been used to document 6 tanks, via hatch access. In addition to the basic CCD analysis system, both standard VHS and Infrared imaging instrumentation were added to provide a comparison of techniques and for use in development of the software imaging & analysis program. Thermal Infrared imaging, however, did not prove to be an effective analytical tool, because of the condensation barrier found on all the coating surfaces and due to the rather small thermal differences associated with coatings defects.

RESULTS AND DISCUSSION

Tank corrosion, brought about by the degradation of the protective barrier coatings, is the primary reason for the refurbishment of ship tanks. As coatings deteriorate over time, there is a corresponding increase in demand placed on the cathodic protection system. While a coatings failure may or may not be related to a corresponding failure of the cathodic protection system, it is certainly accelerated by the deterioration of the protection potential once the cathodic protection resources are exceeded. Cathodic protection, by default, focuses on those areas with highest cathodic demand, such as bare metal, but also is increasingly required by coated surfaces, which slowly degrade, adsorb moisture and suffer from a decreasing dielectric capacity. From a maintenance standpoint, localized coatings deterioration is often not representative of the overall tank condition or even the overall coatings condition. The real question is often not even "How much coatings failure is there?" but "When does this tank require refurbishment?"

Each tank on a ship has a unique geometry, operational use and a set of corresponding environmental factors in which the metals are exposed. Seawater tanks, used in many ballasting operations, are subject to high salinity conditions, high humidity, the attachment of biological materials to the surfaces and repeated fill/drain cycling. Fuel tanks may be purely fuel storage or in many cases they are compensated with seawater, as the fuel is consumed. These conditions continually vary between a petroleum based system to that of seawater immersion. Other tanks, such as sewage and potable water (not considered for this discussion), are both exposed to unique environments. Tanks are coated differently depending on usage and may or may not receive cathodic protection, although all tanks with seawater influx are generally protected. Within the tank, corrosion conditions and coatings performance may vary considerably. Areas in residual water are continually immersed in electrolyte and receive cathodic protection most of the time. Vertical wall areas undergo a wet/dry (damp) cycling and also contain a significant percentage of structural components which are difficult to prepare and coat effectively. Overhead surfaces, while often wet from condensation and high humidity, fail by effects of gravity and osmotic pressure directly at the coatings surfaces. While each of these areas are exposed to similar conditions, in general, failures for different surfaces may occur at different rates and by different mechanisms. Any tank located on the ship exterior may additionally receive solar energy and suffer from highly variable temperature and heat cycling effects.

In seawater, cathodic protection engineers have known that the electrochemical potential of protected steel can be measured using a standard half-cell, such as a silver/silver chloride (Ag/AgCl) reference cell [6]. In a zinc galvanic system, the protected bare steel and even the coated steel surfaces are polarized in an electro-negative direction forcing the steel surfaces to become cathodic with respect to the galvanic anode. As long as sufficient anode mass is correctly located within the structure and the cathodic area requiring protection does not exceed the current capacity of the anodes, then the surfaces will remain protected [7]. Changes in either of these states can be measured using appropriate reference cells installed in the tank. Typically, placement of the zinc anodes in a ballast tank cathodic protection system are weighted 2/3 towards the bottom surfaces of the tank.

The measurement of corrosion properties provides a significant amount of information concerning the state of overall tank preservation. Figure 4, designated as E_{corr} vs. surface area, shows a basic scenario where a rise in cathodic surface area results in the decrease in protection levels for a typical sacrificial anode system. For a given distribution of anodes in a tank, such as the 1.2 ft^2 illustrated, there is a finite amount of current capacity available to protect the coated surfaces. As cathodic area increases, (i.e. a deterioration in coated area) the overall potential of the tank begins to fall off toward more electro-positive potentials. At significant coatings damage percentages, the cathodic protection system is no longer able to maintain potentials at sufficiently negative levels to effectively protect the surfaces, whereby, coatings deterioration will progress at an accelerated rate. Potential measurements, thus, provide a good indication of tank condition, regardless of the method of coatings failure, because the cathodic protection system will compensate for coatings changes.

A tank which has been recently refurbished will have very little surface area to protect and thus reference cells will display potentials at or near zinc levels. As coatings deteriorate, the rate of polarization during filling will remain fairly rapid until one of two events occur. The first would be an increase in the coatings damage percentages, beyond which the anodes would no longer be able to polarize the structure. Hence, the reference cell potentials would begin to drift more electro-positive, as indicated in figure 4. The second condition would pertain to readings observed during the gradual depletion of the sacrificial anodes to the point that the remaining anode mass has insufficient current capacity to polarize the structure. The use of two or more reference cells in the tank, however, provides the ability to track trends in the potential behavior and

to compare variations between individual cells. An analysis of differential reference cell readings can provide some indication as to coatings damage location when a definite trend is identified. If damage is uniform, then the reference cells will likely read similar potentials and rate of polarization. As the damage becomes more localized, the cell nearest the failed coatings will typically shift more electro-positive than the remaining cells.

The curves in figure 5 show an example of a data set for a filling episode in two tanks with widely variable coatings conditions. Historically, these were two adjacent tanks on the same ship, with similar geometry and the same quantity of zinc anodes. The instrumented zinc/reference cell CBM sensors were installed in relatively the same locations with reference cells located 1 m above the bottom and 3 m respectively. The upper curve (a) represents data for a 1-2 year old tank coating, while the lower (b) shows data from a 9-10 year old coating system. In the relatively new condition (a), the reference cell data showed immediate tank polarization along with a corresponding initial zinc current spike. Once polarized the zinc current dropped to a low steady maintenance current of approximately 50 mA. In the deteriorating condition (b), the tank polarized considerably slower and did not achieved the magnitude of polarization nor a steady state within the reported tank filling episode. The corresponding zinc current showed an initial spike nearly 4 times that of figure 5a and then gradually declined to mirror the slow polarization behavior. The final current output, of 150 mA, was still 3 times that of the newly coated tank for the same duration. Comparison of the integrated zinc amp-hrs output indicates a significantly increased consumption of the anode in tank (b) and clearly illustrates the differences in tank condition over the relatively short time period used for this evaluation. The integration area was limited to the area under the curve more electro-negative than -600mV.

Figure 6 shows the upper reference cell data acquired from five different ship tanks using the two reference cell configuration. The five curves were taken during a single filling event and clearly discerned different tank states. The potential levels could be initially graded into three condition rankings, which corresponded to a traffic light scenario where green tanks were trouble free (more electro-negative than -900 mV) and required no maintenance. Tanks which fell into a yellow zone (–750 mV to –900mV) were indicative of increased activity placed on the cathodic protection system and had the requirement for additional current to protect more bare or degrading coatings area. Tanks with nearly freely corroding conditions, fell into the red zone (more electro-positive than -750 mV) and had an unacceptable percentage of corrosion damage. Additionally, the red tanks most likely had a failed or significantly overworked cathodic protection system.

Because this is a filling event, the reference cells begin to read when they become immersed in seawater. The resultant polarization verses time plot provides not only the extent of polarization, but also identifies those tanks that polarize immediately verses those which polarize slowly. Given the fixed tank area and an initial state, each filling episode provides a new polarization curve representative of conditions that currently exist and correspondingly provides trend data for long-term prediction. Detailed analysis of the polarization curve, which is under development, can provide information pertaining to further fine ranking within each of the three major categories and allow for better refinement of coatings damage percentages/tank condition.

The instrumented zinc analysis, as shown in figure 7, added the cathodic protection component into the equation. The tanks with newly painted surfaces and low cathodic protection requirements drew a minimal amount of current from the anode. The initial current demand, along with the subsequent drop-off associated with calcareous deposition, were measured and utilized to provide an indicator for long-term requirements on the system. In the tanks with some coatings breakdown and more exposed metallic area, the anode responded, as expected, and provided an increasing level of current. Once the zinc output exceeded 75 mA, that tank condition was degraded to the yellow condition state and correspondingly, when the output exceeded 175 mA the condition was changed to a red state.

As a coating degrades, there is a gradual reduction in the dielectric nature of the coating barrier, which places increasing demand on the cathodic protection system to protect the surfaces. The current output ultimately increases until a maximum output level is obtained and the system can no longer maintain the same level of polarization. At this maximum output value, both the anode and reference cells provide an indication that the cathodic protection level can not be sustained. In this red condition, the anode current will remain greater than 175 mA, while the potential may fall off to or never move from a freely corroding condition. Tanks in the extreme red condition are most likely sustaining structural corrosion damage and require immediate attention.

Tanks ranked according to potential and current measurement scenario are shown in figures 8-10. The adequate preservation state, i.e. those in the green condition, are relatively easy to identify, both from the data and from visual observation. Under this condition, tanks are readily cathodically protected, well coated and typically have less than 1% coatings damage. No periodic inspection is warranted and no consideration need be given toward maintenance. The marginal preservation state (yellow condition), is beginning to show signs of damage, principally at known problem areas, such as structural support beams and edges. These damage percentages generally are from 1-3% and indicate a "monitor"

situation, where there is still sufficient cathodic protection and no widespread coatings damage. In this state, tanks can be: a) just monitored, b) touched up to improve conditions, c) given additional cathodic protection as the tank polarization drops or d) placed into future scheduled maintenance plans. Additionally, these tanks may receive a remote visual inspection and periodic oversight to track the changes. Once tanks reach a red state, there is considerable coating loss and visually the tanks appear deteriorated.

The traffic light approach is useful for basic tank screening, however, using in-depth analysis and refinement of the polarization behavior, each of these categories can be further subdivided into sub-components. This categorizes and discriminates those tanks which have just entered a major category verses those that are about to be downgraded further. In establishing a 10 point ranking system, tanks can be continuously monitored and tracked over time to augment: 1) changes in monitoring requirements, 2) minor maintenance tasks to improve tanks before severe damage occurs, 3) supplemental cathodic protection needs and 4) establishment of overhaul conditions. Discussion of the criteria used in this analysis is beyond the scope of this paper but is currently in the final phase of development.

Sensor readings provide the objective mechanism to indicate a maintenance state or to establish the requirements for the implementation of remote visual inspection. Figure 11 shows a comparison of a visual tank image with one that has been computer analyzed to estimate the coatings damage percentages. The spectrographic analysis program can be systematically used to identify corroded surfaces, based on spectral color differences, geometry, pattern recognition, and texture. Spectral discrimination provides the ability to distinguish between corrosion product, rust staining and biological/scum deposits on the tank walls. Using an automated tracking system, the visual analysis can be repeated multiple times in an objective manner, using the computer to set the camera location and magnification. Both images and analyses are used to track the changes in tank condition over time and can be integrated to evaluate changes in damage percentages by subtraction techniques. Results are correlated with that received from the in-situ sensor trend analysis. From a life-cycle standpoint, an engineer receives image analysis data that can be correlated with quantitative sensor data and used ultimately to support maintenance decisions, without the necessity of manned entry into the tank.

CONCLUSIONS

This work is currently an on-going program incorporating R & D tasking, field trials and ship tests. Data received to date highlights the complex operational aspects and diversity of ballast tank usage and the advantages of a condition based verses a time based maintenance approach. Reference cell tank sensors have proven to be good indicators of overall tank coatings quality and have good capability for determining general tank condition, especially when combined with periodic remote visual inspections. The current research effort is toward sensor commercialization, software analysis refinement, inspection equipment development and spectrographic analysis techniques.

Once the database is completed, tank condition will be screened and ranked to categorize maintenance into three basic requirements, that of: 1) no maintenance required, 2) touch-up and light repair and 3) refurbishment. Sub categories within each group will target differences in maintenance approach and add a rate of change component to the formula. Integration of the software will provide real-time monitoring, trend analysis, documentation and inspection reporting at a level where minimally trained personnel can understand the concepts. This husbandry approach will enable port engineers or maintenance personnel to adequately monitor tank preservation and make decisions based on quantitative data and documentation. This will optimize maintenance scheduling, cost savings and prevent needless overhaul. Future phases of this work already include permanent installation of tank sensors into fleet ships and the implementation of the inspection platforms for periodic visual tank analysis.

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TABLE 1
TECHNOLOGIES INVESTIGATED FOR ASSESSMENT OF SEAWATER BALLAST AND COMPENSATING FUEL TANKS ABOARD US NAVY SHIPS

Technique	Pro	Con
Microwave, Near And Far Field	Near field technology promises hand held device for micro inspection	Microwaves effected by water, tank structures and moisture on walls
Optical Coherent Tomography	Ability to detect coatings disbondment	Micro area analysis
Optical Visible Light	Ability to document damage and retain good color rendering	Requires supplemental lighting
Color Visible Imaging/CCD	Real-time Spectrographic analysis, visual record/documentation, reliable and durable	Analysis program required
Infrared Spectrometer	Ability to provide area damage documentation and some localized features	Affected by temp variation/moisture/ silt/ salinity barrier on tank walls Limited Effectiveness
Ultra Sound	Holds promise in near future	Affected by tank structure
Fiber Optic Corrosion Monitors	Ability to monitor and detect corrosion initiation sites	Monitors micro areas
Color Visible Imaging/CCD	Real-time Spectrographic analysis, visual record/documentation, reliable	Analysis program required
Electrochemical Impedance Spectroscopy	Determine coatings porosity and relative coatings properties	Localized information, complex installation and limited interpretation
Electrochemical Reference Cell	Currently utilized in seawater ballast and compensating fuel tanks	Requires electrolyte for operation
Coating Fluorescing Dyes	Ability to detect holidays in surface coatings	Not proven inspection method and not applicable to old tanks

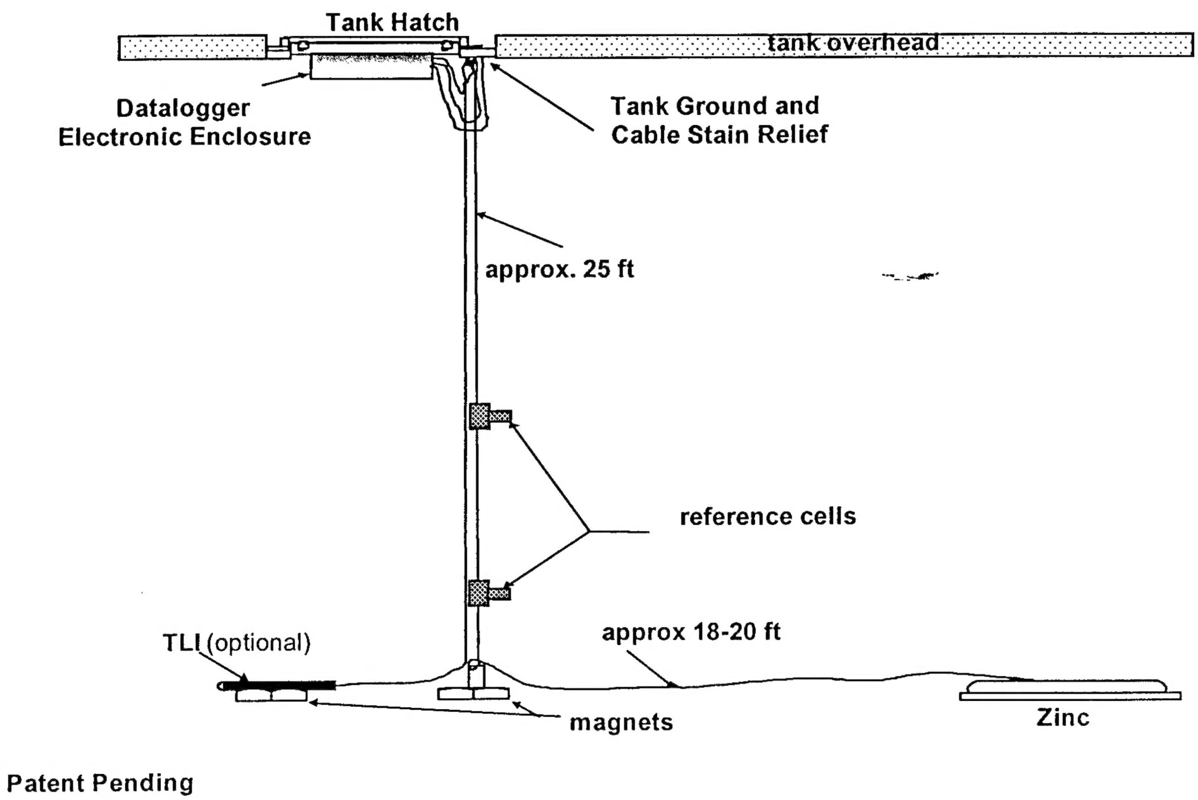


Figure 1. Schematic Drawing of Tank Sensor Installation in Seawater Ballast Tank.

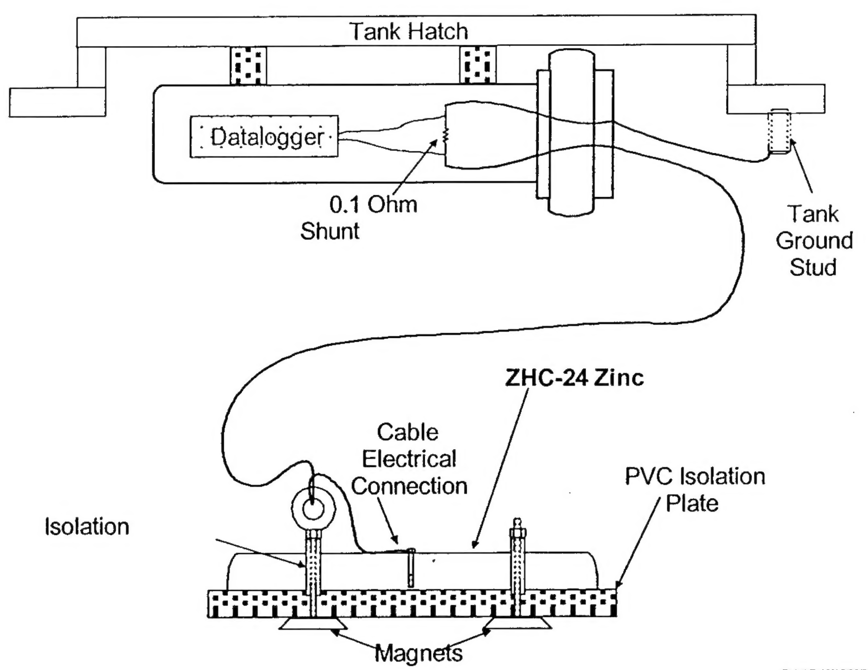


Figure 2. Schematic of Instrumented Zinc Anode for Current Output Monitoring.

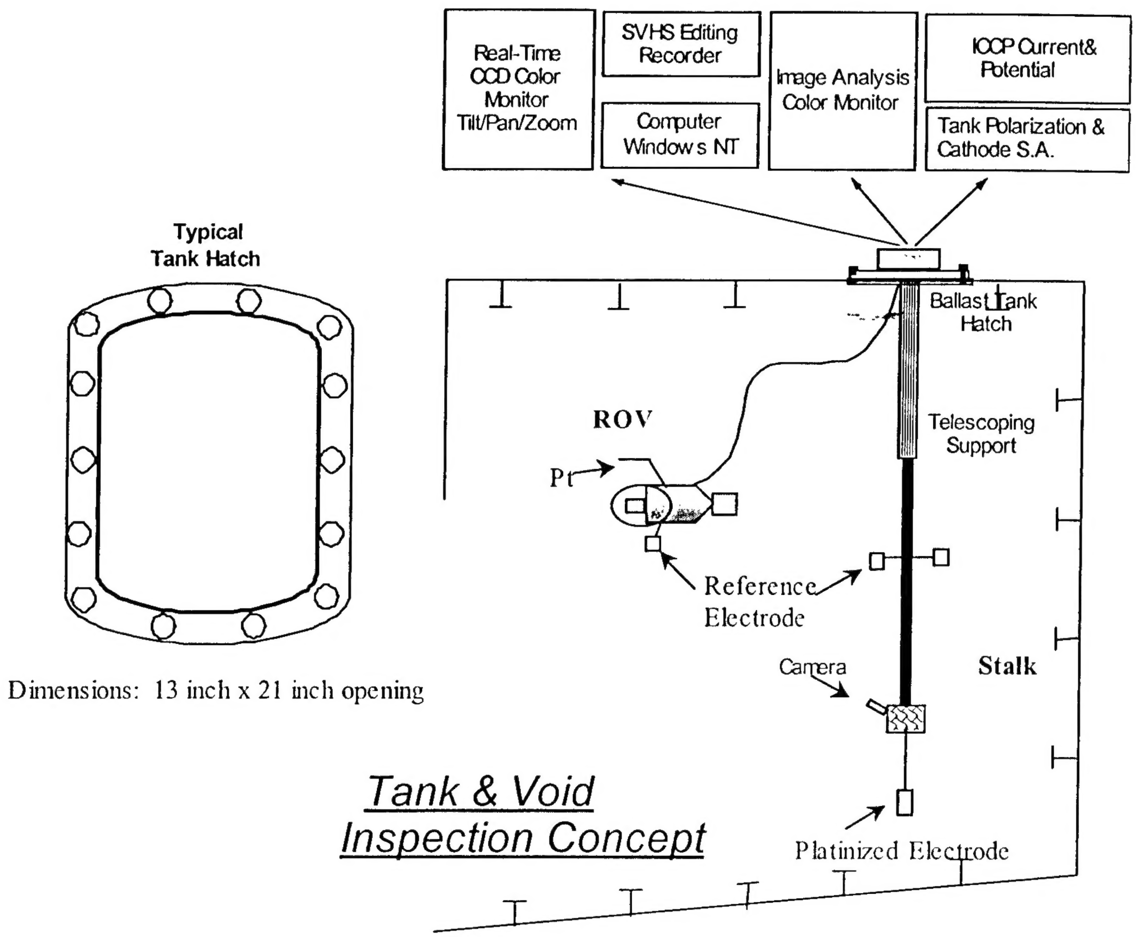


Figure 3. Schematic Drawing of Hatch Insertable Inspection Platform and Representative ROV Coatings Inspector.

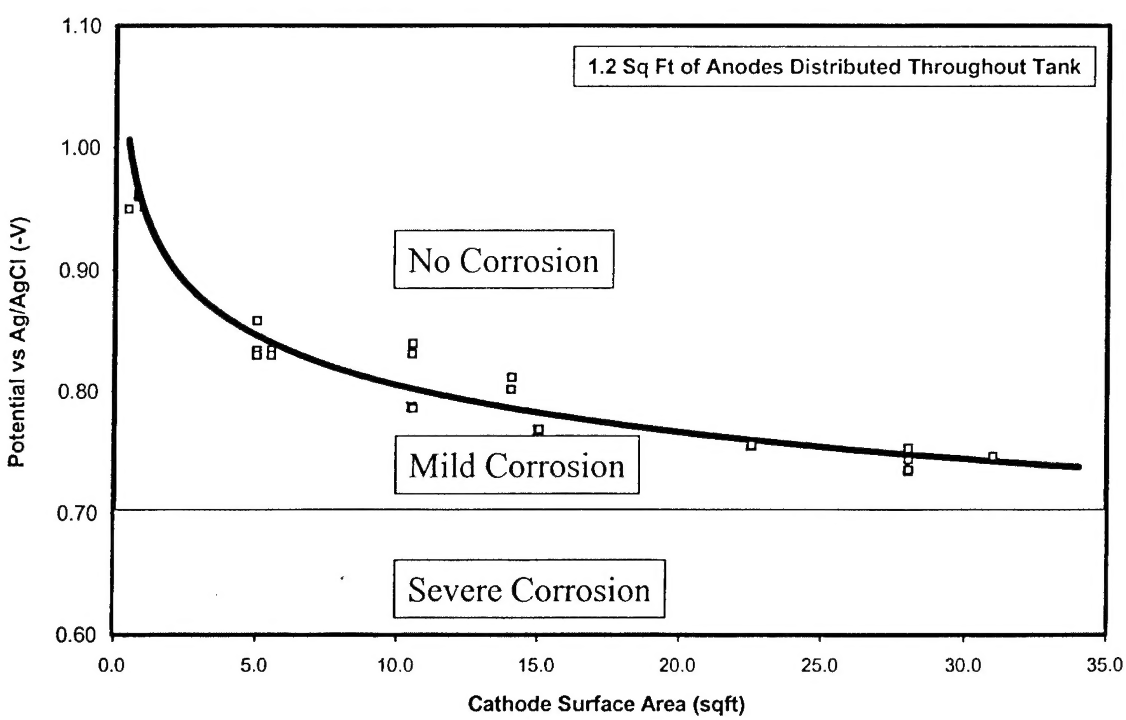
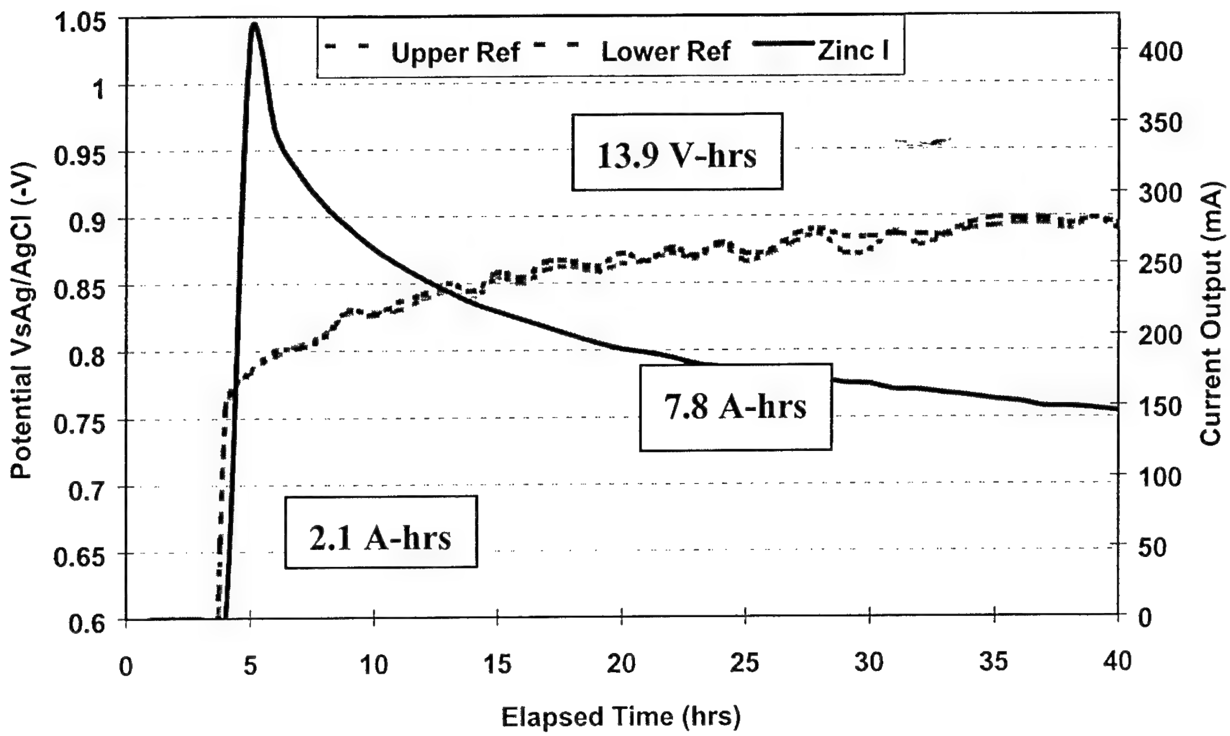


Figure 4. Corrosion Concept for Basic Tank Analysis Using Polarization Verses Cathodic Surface Area Ratio.



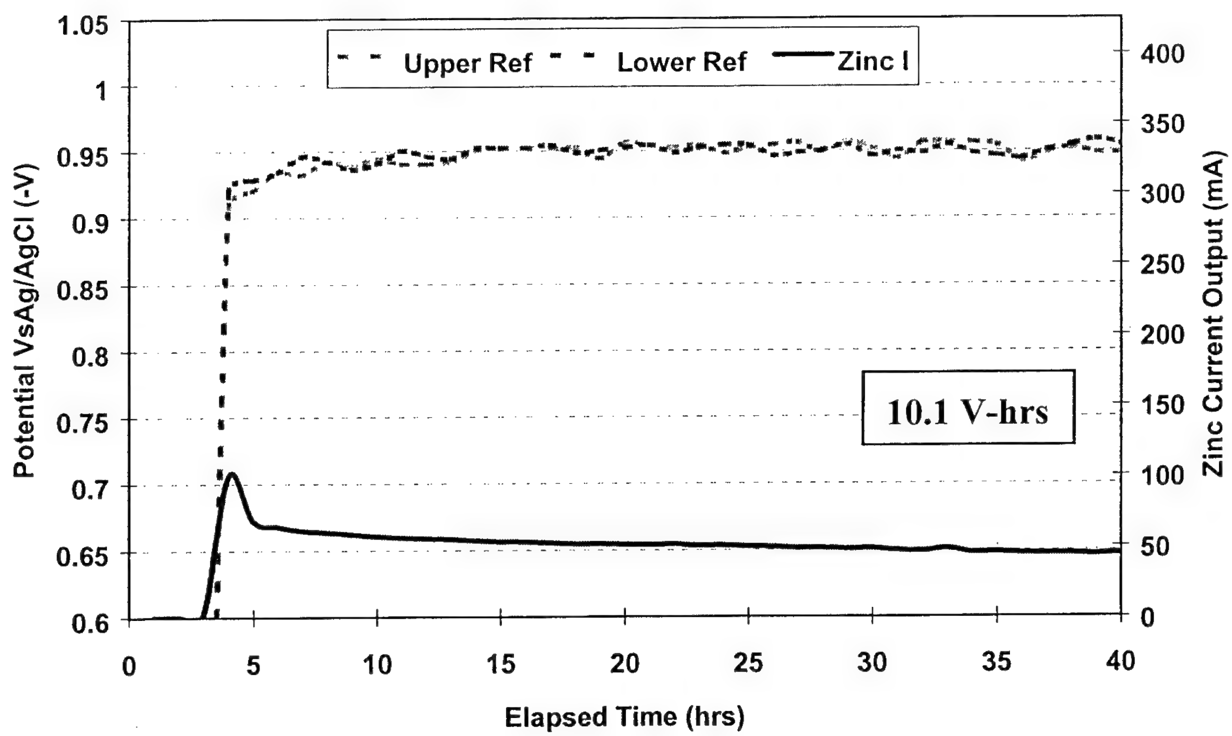


Figure 5. (a) Top - Shows Potential and Instrumented Zinc Data for 1-2 Year Old Tank Coating, (b) Bottom - Shows Potential and Instrumented Zinc Data for 9-10 Year Old Coating.

Condition Ranking	E_{stable} Stable Potential Post 10 hrs
Green	more negative than -900 mV
Yellow	Between -750 and -900 mV
Red	less negative than -750 mV

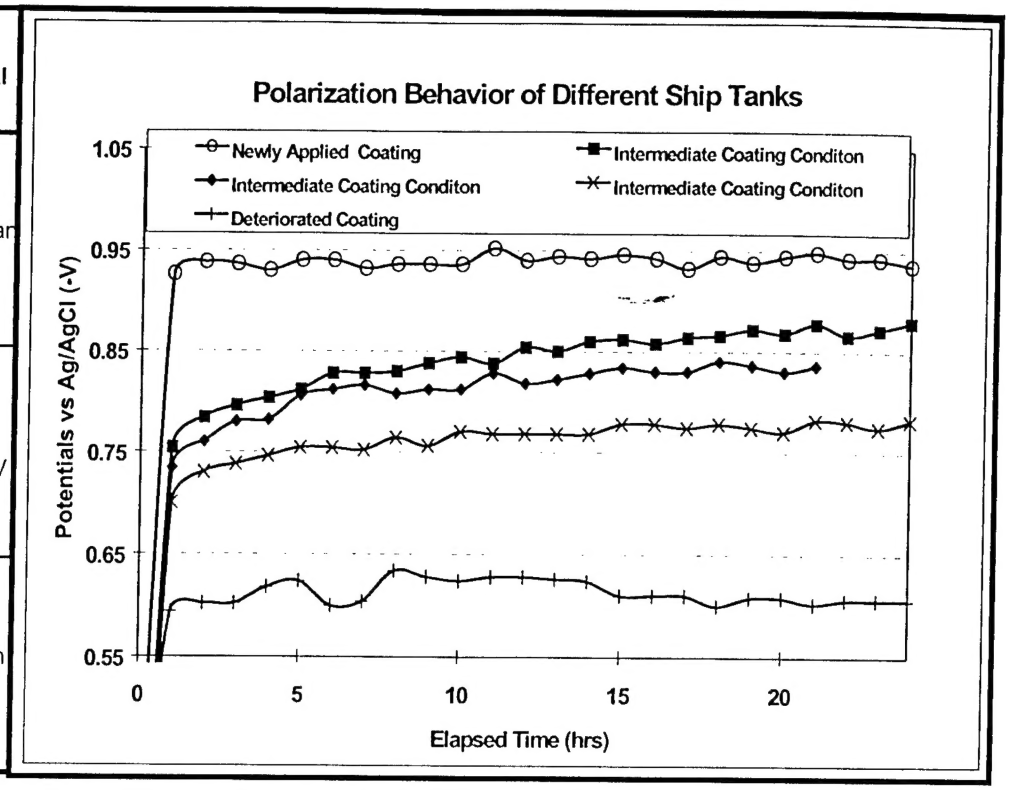


Figure 6. Basic Tank Condition Ranking Using Potential Verses Time Data.

Condition Ranking	I Stable Stable Zinc Output Post 10 hrs
Green	Low Current < 75 mA
Yellow	Med Current 75-175 mA
Red	Hi Current > 175 mA

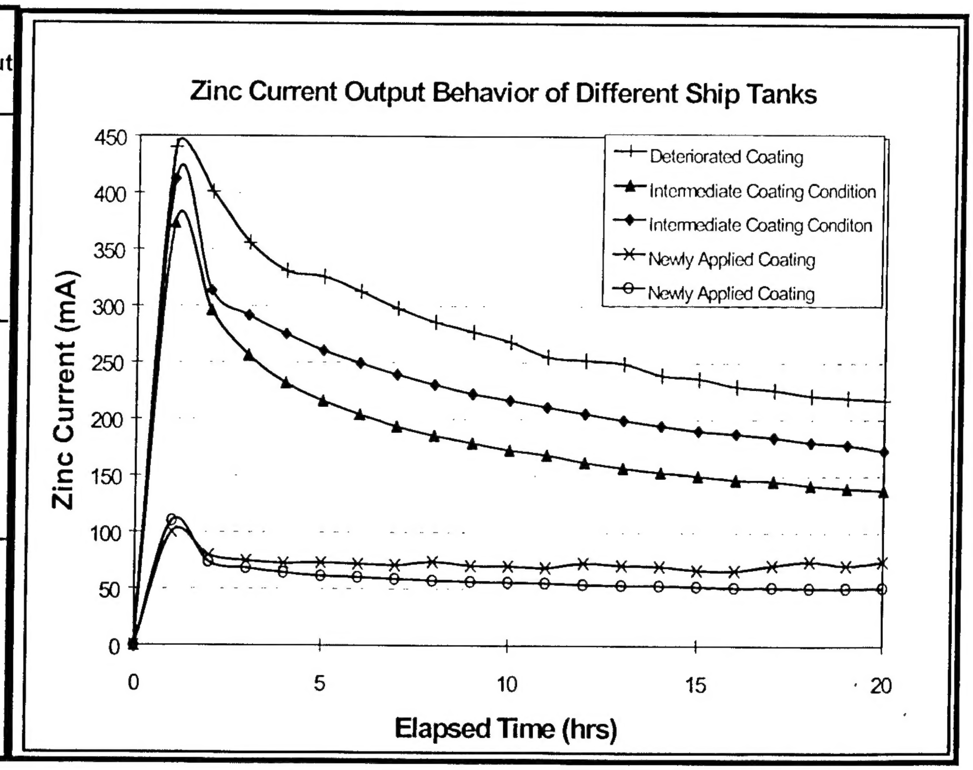


Figure 7. Basic Tank Condition Ranking Using Zinc Anode Current Output Verses Time.

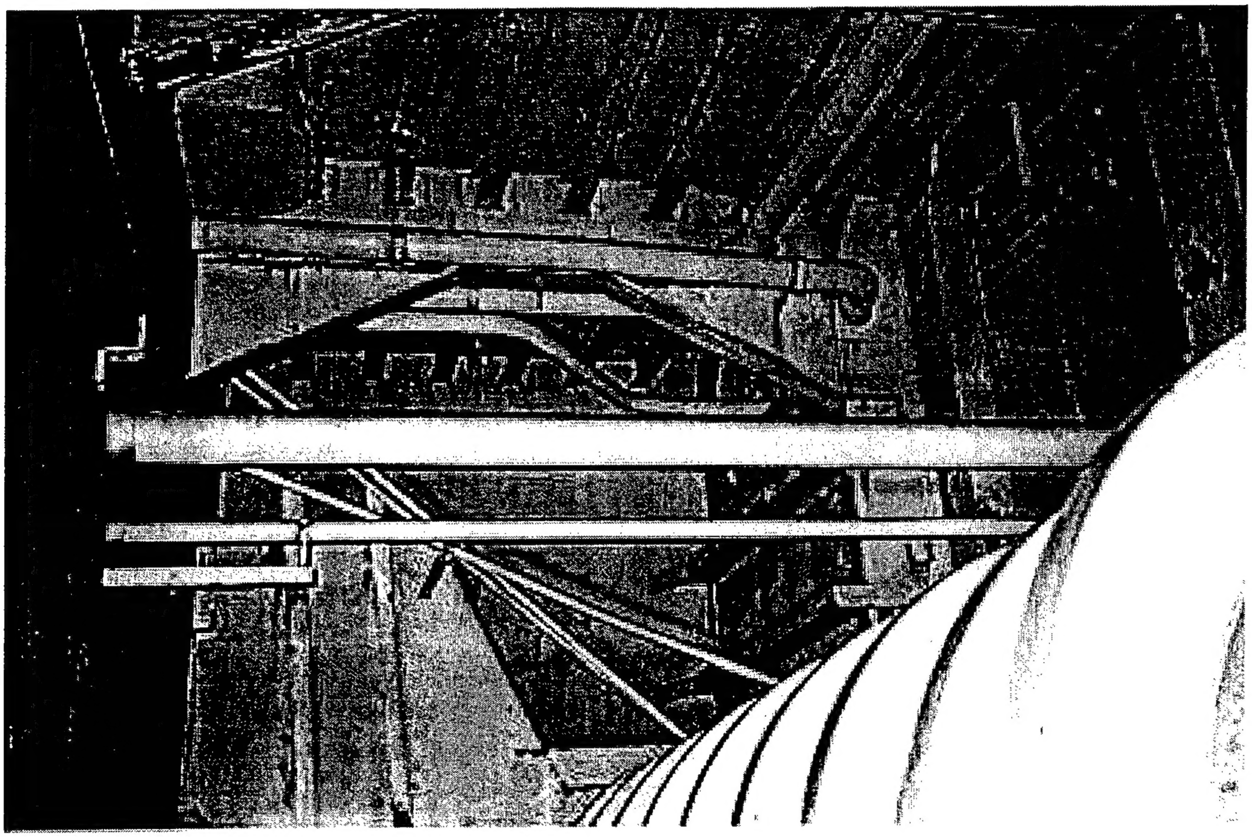


Figure 8. Photograph of "Green" Ballast Tank After 18 Months Service.

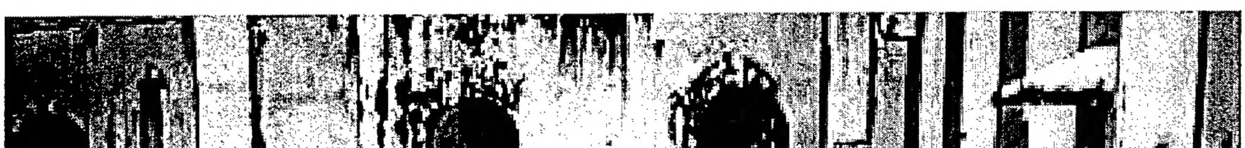


Figure 9. Photograph of "Yellow" Ballast Tank After 11 Years Service.

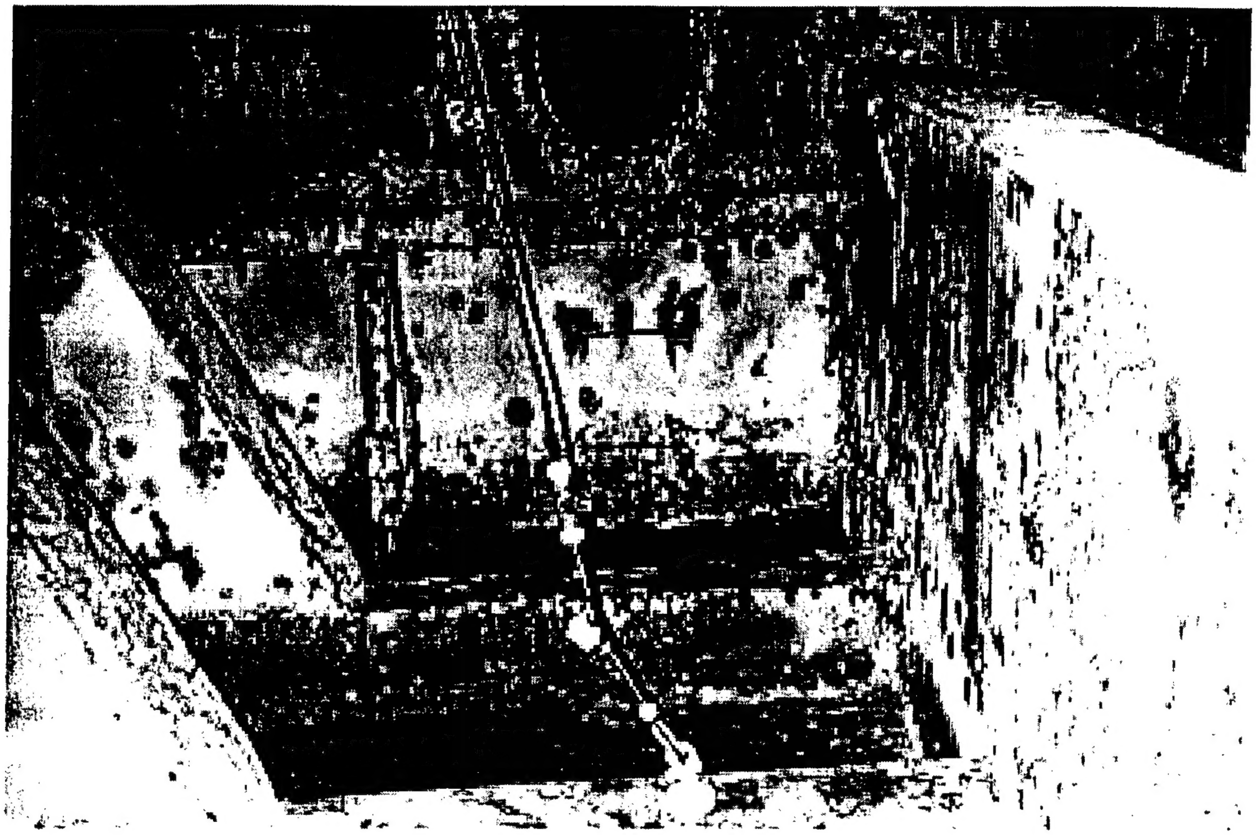


Figure 10. Photograph of "Red" Ballast Tank After 11 Years Service.

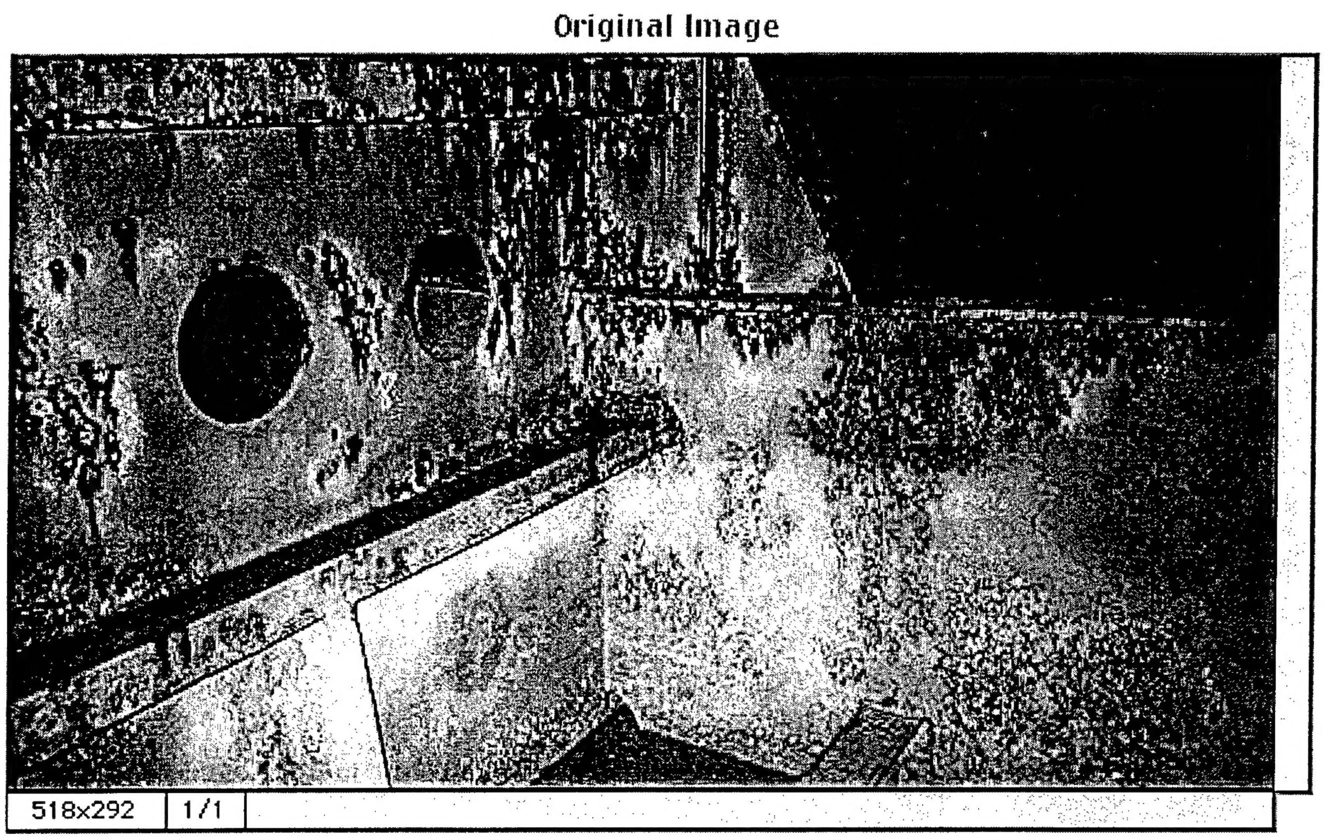


Figure 11. Comparison of Photographic Image (top) With Identical Image Having Spectrographic Area Analysis (bottom).